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ABSTRACT

This paper describes how electronic spreadsheet simulators, originally designed to simulate and replace large paper worksheets used in accounting and financial planning, can be used to study and explore functional relationships among a number of parameters. As a way of providing a context for understanding this application of a spreadsheet template, a description of the use of electronic spreadsheets to enable students to conduct simulated microelectrode recording experiments is given. Also described is the use of spreadsheet simulators to let students explore the operation of models of hypothetical neural networks which underly such visual phenomena as induced color contrast. Student comments on the neural model simulations indicate that a pre-use discussion and post-use debriefing, in lecture or tutorial sessions, seem to enhance the effectiveness of the simulations; some limitations of the simulations can be compensated for by proper pre-use preparation and post-use debriefing; and many students feel they gain an enhanced depth and quality of understanding from the interactive learning and immediate feedback. (THC)

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Using an Electronic Spreadsheet Simulator to Teach Neural Modeling of Visual Phenomena

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ABSTRACT

An electronic spreadsheet simulator can be used to enable students to conduct simulated microelectrode recording experiments. In addition, it can be used to let students explore the operation of models of hypothetical neural networks which underly such visual phenomena as induced color contrast.

KEYWORDS: spreadsheet simulator, microcomputers in education, neural modeling, neural networks

Using an Electronic Spreadsheet Simulator to Teach Neural Modeling of Visual Phenomena*

While many microcomputer programs intended for instructional purposes seem to be impractical or of little use at the College and University level when every student has a personal machine [1], required student ownership of a personal computer opens up new opportunities for the use of microcomputer applications programs. One example involves the electronic spreadsheet simulator (*e.g.*, Multiplan, SuperCalc, VisiCalc, *etc.*). Originally designed to simulate and replace the large paper worksheet used in accounting and financial planning, the spreadsheet simulator is a more generally useful tool which can be used to study and explore functional relationships among a number of parameters. Consequently it can be used in fields as diverse as ecology [2], nutrition, physics, and psychology [3].

The electronic spreadsheet is oriented around a matrix of rows and columns, into which the user enters text, data, formulas or instructions which tell the program to look up a value from another location and then use it in a calculation or in some other way. The program executes user specified calculations either automatically, after a new value is entered anywhere in the matrix, or upon demand. This calculation cycle often involves re-calculation of new values for previously entered formulas that depend upon still other values that may have been changed during or since the last calculation cycle. The typical spreadsheet simulator also offers some limited programming language capabilities, including the ability to manipulate strings and to do interative calculations. In addition, built-in functions can be combined to produce a limited plotting capability, thereby providing both a graphical and a numerical method for illustrating relational concepts. Although the spreadsheet program requires that the simulation designer be able to specify the relationships to be explored, it does not require that the end-user be a programmer.

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*This paper will appear in a future issue of *Collegiate Microcomputer*.

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Extending an approach developed by Lindsay and Norman [4], a recent paper by Hewett [3] illustrated some ways in which the spreadsheet simulator could be used in teaching students how to model the kinds of neural circuits and neural networks which may underly and be responsible for a variety of visual phenomena. Although a claim was made that relatively complex neural networks could be modeled using the electronic spreadsheet simulator, the actual examples used were fairly simple. It is the purpose of this paper to develop a more complex example of how a hypothetical network of neural cells and its effects can be modeled using the electronic spreadsheet.

Microelectrode Recording

As a way of providing a context for understanding this application of a spreadsheet template, it is useful to review one of the basic examples provided by Hewett [3]. For many who study sensation, perception and pattern recognition in human beings, certain kinds of comparative neurophysiological and neuropsychological information play a fundamental role in theoretical modeling. A portion of this information is derived from work with non-humans and is done by recording the output of a single nerve cell with a microelectrode. Given similar neuroanatomy and similar patterns of behavior in response to similar stimuli it is assumed that the results of these microelectrode recording experiments can be generalized to humans. Thus, these experimental results provide an understanding of basic conceptual building blocks which can be used in a variety of theoretical models of neural processes in humans.

Now, consider the following heuristic simplification. A typical microelectrode recording experiment involves inserting a microelectrode into a nerve bundle in an attempt to pick up the neural impulses generated by a single fiber, for example, a single ganglion cell fiber in the optic nerve. Once the investigator has isolated a single transmitter neuron, differing patterns of stimulation are introduced to the receptors. Then an attempt is made to discover meaningful relationships by comparing patterns of receptor cell stimulation with their effect on recorded transmitter cell output.

Assume the output of a single transmitter is being recorded. Often with no receptor stimulation this type of cell will show a background firing rate. A further simplification of this situation can be introduced by focusing on a single, one cell wide slice of neural tissue. By temporarily stimulating each individual receptor, observed changes in the firing pattern of the transmitter can be attributed to the effect of the receptor. A similar result can be obtained by moving a square wave of light from one end to the other over the set of receptors. Either procedure allows identification of receptor cells that are part of the neural circuit, *i.e.*, the receptors influencing the transmitter being recorded. It is also possible to identify whether the effect of a receptor is excitatory, making the transmitter firing rate increase, or inhibitory, making the transmitter rate decrease. Finally, it is possible to determine the strength of the effect, that is, how much of the receptor firing rate gets passed on to the transmitter.

As described in an earlier paper [3], one way of simulating this situation is represented in Figure 1, which is the screen display from an Apple

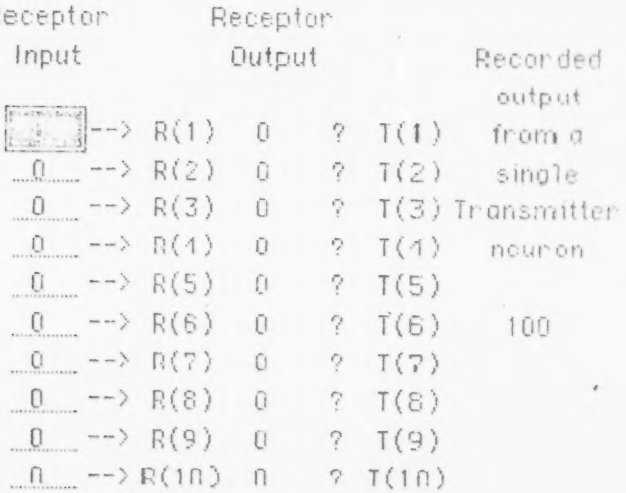
Receptor Input
Receptor Output
Recorded output from a single Transmitter neuron
100
--> R(1) 0 ? T(1)
0 --> R(2) 0 ? T(2)
0 --> R(3) 0 ? T(3)
0 --> R(4) 0 ? T(4)
0 --> R(5) 0 ? T(5)
0 --> R(6) 0 ? T(6)
0 --> R(7) 0 ? T(7)
0 --> R(8) 0 ? T(8)
0 --> R(9) 0 ? T(9)
0 --> R(10) 0 ? T(10)

Fig. 1

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Macintosh running Microsoft Multiplan. Several values indicating the number of units of light stimulating each of a set of receptor cells appear in the first column. Next, the display represents a one cell wide slice of neural tissue with two kinds of neural cells--receptors and transmitters. Adjacent to the receptors is a column for the most recently calculated output of each receptor. Beside the transmitters is a column of question marks. The question marks symbolize a lack of knowledge about the nature and number of connections between the two layers of cells. Finally, there is a single value representing the most recently calculated firing rate of the single transmitter neuron being recorded. The reader should take care to note that the firing rates of all neurons used here, and in the more complex simulation discussed below, are intended to illustrate relationships rather than to duplicate observed experimental values. Furthermore, these simulations are intended to be functionally equivalent, rather than isomorphic, with the actual neural circuitry. This means that a number of complexities which do not contribute to an understanding of the operation of the neural circuitry have not been included in the simulation.

In the formula which the spreadsheet program uses to calculate the total firing rate for the transmitter there is a constant representing the background firing rate of the transmitter and a set of additional values, each representing the effects of a receptor. Every formula entry for a receptor is the product of a constant and a receptor firing rate value. The receptor firing rate is specified by identifying another spreadsheet location which the program uses to look up the receptor output value. That value is then used by the program in its calculations. Each constant is a gain factor between 1.0 and -1.0. A positive gain factor value represents an excitatory neural connection, a negative value, an inhibitory one. The absolute value of a gain factor determines the percentage of the receptor firing rate which is passed on to the transmitter being recorded.

By providing an appropriate pattern of stimulation to the receptors the template user can discover the neural circuit. For example, Figure 2

Receptor Input			Receptor Output			
						Recorded output
100	-->	R(1)	100	?	T(1)	from a
100	-->	R(2)	100	?	T(2)	single
100	-->	R(3)	100	?	T(3)	Transmitter
100	-->	R(4)	100	?	T(4)	neuron
100	-->	R(5)	100	?	T(5)	
	-->	R(6)	0	?	T(6)	90
0	-->	R(7)	0	?	T(7)	
0	-->	R(8)	0	?	T(8)	
0	-->	R(9)	0	?	T(9)	
0	-->	R(10)	0	?	T(10)	

Fig. 2

represents a screen display simulating the situation that exists after a user has begun to pass a square wave of light over the receptors. (Receptor input values are in the number of units of light required to produce 100 impulses per second in the receptors.) The spreadsheet is set for automatic calculation, which means that each time the user enters another value the program automatically calculates or recalculates every other value.

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At this point the user has just entered an input to the 5th receptor cell. Entering the first, the second, the third and the fourth inputs produced no changes in the transmitter firing rate. Now, however, transmitter firing rate has dropped to 90 impulses per second. This is a decrease by 10% of the fifth receptor cell's output and indicates two things. First, receptor five has an inhibitory effect. Second, the gain is -0.1 for this connection. Continuing would allow the user to discover that stimulating the 6th receptor with 100 units of light increases the transmitter firing rate to 190; that the same stimulation of the 7th receptor decreases the transmitter rate to 180; and that similar changes for the 8th, 9th, and 10th receptors produce no effect on the transmitter.

Given this information, a user of this spreadsheet template should be able to draw a diagram of a simple neural circuit in which receptors five and seven, with gains of -0.1, have inhibitory effects and receptor six , with a gain of 1.0, has an excitatory effect. After running the "experiment" described above, a student who has discovered this simple circuit can now be provided with a series of increasingly more complex "unknown" circuits which the instructor can create by modifying the formula that calculates the transmitter firing rate. Furthermore, the student is now ready to deal with the additional complexities of a variety of neural networks which can be simulated using the basic components described above. Working within the constraints imposed by known information about human neurophysiology, neuranatomy, and behavior, these basic building blocks can be used to model the neural processes underlying a variety of visual phenomena.

Induced Color Contrast

For example, given the computational capabilities of an electronic spreadsheet, neural model simulations can easily involve the output of several transmitter cells and more than two layers of cells. This additional complexity allows the creation of neural network simulations composed of multiple circuits and of more than one type of circuit. Consider the process of lateral inhibition thought to be responsible for visual phenomena such as the induced color contrast effect. There are two ways to observe this effect. One involves

putting small patches of a bright color against different backgrounds, where each background has a constant color that differs from the color of the patch and from the color of the other backgrounds (*e.g.*, a patch of red against an orange background, another patch of red against a yellow background, another against a green background, and another against a blue background). If the patch is small enough, each patch of red appears to vary slightly in color from one background to another.

A second way to observe induced color contrast involves putting a color patch against a homogeneous background color. For larger patches, the intensity of the colors at the edge, where the transition between the patch and background occurs, appears to differ slightly from that observed elsewhere on the patch or the background. This effect is strongest with complementary pairs of colors, *e.g.*, a red patch against a green background.

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One way of using a spreadsheet simulator to model the underlying neural network thought to be responsible for this effect is represented in Figure 3. In this figure there are three layers of neural cells represented. The

Receptor Input		Receptor Output	Layer 1 Transmitter Output	Layer 2 Transmitter Output
0	--> Red(1)	0		
0	--> Green(1)	0	T(1) 200	T(1) 220
0	--> Red(2)	0		
0	--> Green(2)	0	T(2) 200	T(2) 220
0	--> Red(3)	0		
0	--> Green(3)	0	T(3) 200	T(3) 220
0	--> Red(4)	0		
0	--> Green(4)	0	T(4) 200	T(4) 220
0	--> Red(5)	0		
0	--> Green(5)	0	T(5) 200	T(5) 220
0	--> Red(6)	0		

Fig. 3

first is a layer of receptor cells, the next two are layers of transmitters. There are two types of receptor cells shown here, one set sensitive to red light, the other set is sensitive to green light. Scrolling the window downwards would reveal that there are a total of 12 pairs of receptors, 12 layer one transmitters and 12 layer two transmitters.

For purposes of this example the receptor pairs, the transmitters, and the neural circuits in the network are assumed to extend indefinitely beyond those at either end of the set represented in the spreadsheet template. The light input for the last receptor pair at either end of the set shown is also assumed to extend indefinitely as well. Again, the reader should take care to

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note that the firing rates of all neurons used here are intended to illustrate relationships rather than to duplicate observed experimental values. Furthermore, these simulations are intended to be functionally equivalent, rather than isomorphic, with the actual neural circuitry. This means that a number of complexities which do not contribute to an understanding of the operation of the neural circuitry have not been included in the simulation.

In Figure 4 two receptors, Red(3) and Green(3), are being stimulated by the number of units of light required to produce a firing rate of 100

Receptor Input		Receptor Output	Layer 1 Transmitter Output	Layer 2 Transmitter Output
0	--> Red(1)	0		
0	--> Green(1)	0	T(1) 200	T(1) 220
0	--> Red(2)	0		
0	--> Green(2)	0	T(2) 200	T(2) 220
100	--> Red(3)	100		
100	--> Green(3)	100	T(3) 200	T(3) 220
0	--> Red(4)	0		
0	--> Green(4)	0	T(4) 200	T(4) 220
0	--> Red(5)	0		
0	--> Green(5)	0	T(5) 200	T(5) 220
0	--> Red(6)	0		

Fig. 4

impulses per second in each receptor. The 100 units of stimulation to the "red" receptor, Red(3), are assumed to be from red light and the 100 units to the "green" receptor, Green(3), are assumed to be from green light. Comparision of Figure 4 with Figure 3 reveals that while the stimulation has increased the firing rates of the two target receptors, there is no other obvious effect on the network. This results from the fact that Red(3) and Green(3) are "opponent process" neurons, having opposing and balanced effects on the third

transmitter in the first layer. The need for some kind of relationship such as this can be seen by remembering that a model of the human visual system must be able to respond differently to differing intensities of red light and to differing intensitites of green light, while being able to "ignore" the presence of equal intensities of those wavelengths in white light.

Stimulation of only one of these receptors at a time, either Red(3) or Green(3), produces different and differing effects on the network. Figure 5

Receptor Input		Receptor Output	Layer 1 Transmitter Output	Layer 2 Transmitter Output
0	--> Red(1)	0		
0	--> Green(1)	0	T(1) 230	T(1) 230
0	--> Red(2)	0		
0	--> Green(2)	0	T(2) 200	T(2) 230
[illegible]	--> Red(3)	0		
100	> Green(3)	100	T(3) 130	T(3) 120
0	--> Red(4)	0		
0	> Green(4)	0	T(4) 230	T(4) 230
0	--> Red(5)	0		
0	--> Green(5)	0	T(5) 200	T(5) 230
0	--> Red(6)	0		

Fig. 5

shows the network when a single red receptor, Red(3), is being stimulated by the number of units of red light required to produce 100 impulses per second in that receptor. By comparing Figure 5 with Figure 3 it can be seen that stimulation of this receptor shows up in the first layer transmitters with only one effect, an excitatory one on the third transmitter. Given the change in the output of this cell relative to the output of the receptor, it can be seen that the gain is 1.0 since the transmitter firing rate increases by 100% of the receptor cell firing rate.

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Moving from the first to the second layer of transmitters, there is a much more widespread effect. Again, comparing Figure 5 with Figure 3, it can be seen that in the second layer of transmitters the first, second, fourth and fifth transmitter firing rates have decreased by 10% of the increase in the firing rate of the first layer transmitter, T(3). In addition, the firing rate of third transmitter in the second layer has increased by 100% of the change in firing rate of the third transmitter in the first layer . There are no other changes in the network.

A somewhat different set of effects is produced in the network if a single "green" receptor is stimulated. Figure 6 shows the network when only

Receptor Input		Receptor Output	Layer 1 Transmitter Output	Layer 2 Transmitter Output
0	--> Red(1)	0		
0	--> Green(1)	0	T(1) 200	T(1) 210
0	--> Red(2)	0		
0	--> Green(2)	0	T(2) 200	T(2) 210
100	--> Red(3)	100		
	--> Green(3)	0	T(3) 300	T(3) 320
0	--> Red(4)	0		
0	--> Green(4)	0	T(4) 200	T(4) 210
0	--> Red(5)	0		
0	--> Green(5)	0	T(5) 200	T(5) 210
0	--> Red(6)	0		

Fig. 6

the third green receptor, Green(3), is stimulated. By comparing Figure 6 with Figure 3 it can be seen that stimulation of this receptor shows up in the first layer transmitters with only one effect, an inhibitory one on the third transmitter. Given the change in the output of this cell relative to the output of the receptor, it can be seen that the gain is -1.0 since the decrease is 100% of the receptor firing rate.

Moving from the first to the second layer of transmitters, there is a much more widespread effect. Again, comparing Figure 6 with Figure 3, it can be seen that in the second level of transmitters the first, second, fourth and fifth transmitter firing rates have increased by 10% of the decrease in the firing rate of the first layer T(3). Since the firing rate of the first layer transmitter has gone down, the effect in the second layer results from a reduction in inhibition of the transmitters in the second layer. In addition, the firing rate of third transmitter in the second layer has gone down by 100% of the change in firing rate of the first layer transmitter. Since the firing rate of the first layer transmitter has gone down, this effect in the second layer results from a reduction in the excitation of the layer two transmitter. There are no other changes in the network.

As a result of patterns of stimulation tested so far it can be seen that the two receptors, Red(3) and Green(3), along with the single transmitter they influence--T(3) in layer one--form a neural circuit in which one receptor excites the transmitter and the other inhibits it. This same relationship exists for each pair of receptors and a first layer transmitter, *e.g.*, Red(8), Green(8) and the layer one T(8). Similarly, there is a "standard" or typical neural circuit conneting cells in the first and second layer of transmitters. The third transmitter in layer one has a strong excitatory effect on the third transmitter in layer two. It also has small inhibitory effects on four other layer two transmitters. This same relationship holds for the effects of each layer one transmitter on second layer transmitters, *e.g.*, the seventh transmitter in layer one has a strong excitatory effect on the seventh transmitter in layer two and small inhibitory effects on the fifth, sixth, eighth, and ninth transmitters in layer two.

The effects of stimulating this network of cells with a more complex pattern of light can be seen in Figures 7 and 8. While only a portion of the spreadsheet can actually be seen in each figure, looking at both reveals that the first and last four pairs of receptors (1-4 and 9-12) are being stimulated with green light only. The middle four pairs of receptors (5-8) are being stimulated with red light only. This represents the pattern of stimulation occuring when a patch of red is viewed against a green background.

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```
  0 --> Red(1)    0
100 --> Green(1)  100      T(1) 100      T(1) 160
  0 --> Red(2)    0
100 --> Green(2)  100      T(2) 100      T(2) 160
  0 --> Red(3)    0
100 --> Green(3)  100      T(3) 100      T(3) 140
  0 --> Red(4)    0
100 --> Green(4)  100      T(4) 100      T(4) 120
100 --> Red(5)    100
  0 --> Green(5)  0        T(5) 300      T(5) 320
100 --> Red(6)    100
  0 --> Green(6)  0        T(6) 300      T(6) 300
100 --> Red(7)    100
  0 --> Green(7)  0        T(7) 300      T(7) 300
100 --> Red(8)    100
```

Fig. 7

```
  0 --> Green(5)  0        T(5) 300      T(5) 320
100 --> Red(6)    100
  0 --> Green(6)  0        T(6) 300      T(6) 300
100 --> Red(7)    100
  0 --> Green(7)  0        T(7) 300      T(7) 300
100 --> Red(8)    100
  0 --> Green(8)  0        T(8) 300      T(8) 320
  0 --> Red(9)    0
100 --> Green(9)  100      T(9) 100      T(9) 120
  0 --> Red(10)   0
100 --> Green(10) 100      T(10) 100     T(10) 140
  0 --> Red(11)   0
100 --> Green(11) 100      T(11) 100     T(11) 160
  0 --> Red(12)   0
100 --> Green(12) 100      T(12) 100     T(12) 160
```

Fig. 8

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Comparing the patterns of cell outputs for receptors, layer one transmitters, and layer two transmitters a student can begin to see the results of the excitatory and inhibitory effects throughout the entire network. Of more interest, however, are the effects of different kinds of receptor stimulation upon the firing rates for the second layer transmitter cells. Looking at the first four transmitters in this layer it can be seen that all are below the 220 impulse per second firing rate shown in Figures 3 and 4, thereby indicating to the brain the presence of green light. The same is true for the last four transmitter cells in the second layer. The middle four second layer transmitter cells all have a firing rate above the 220 impulse per second firing rate, thereby indicating the presence of red light. The "edge" or transition between the two types of light occurs between the fourth and fifth transmitters in each layer. Because there are no lateral effects from the receptors to the first layer of transmitters the transition between the effects of the two types of stimulation--red and green light--is as sharp in the first layer of transmitters as it is in the input to the receptors.

Looking at the second layer of transmitters, however, reveals a different picture. Here, because of the lateral connections existing between the first and second layers the effect of the transition between the two kinds of light stimulation to the receptors takes on a different pattern, with the transmitter outputs indicating a green which shows a gradual change in intensity as one moves toward the edge of the dividing line between the two different wavelenghts of light. Similarly, the level two transmitters indicate a change in the intensity of the red light. A similar pattern can be seen between the last four and middle four receptor pairs and transmitters. Although the actual neural circuitry is almost certainly much more complex in detail, this model helps to explain why a homogeneous patch of red appears to vary in intensity when viewed against a green background.

To create a visual representation of this pattern of values, several spreadsheet locations can each be assigned a formula which refers to a second layer transmitter output value, and which utilizes the string manipulation capability of the spreadsheet program. In Figure 9 the window

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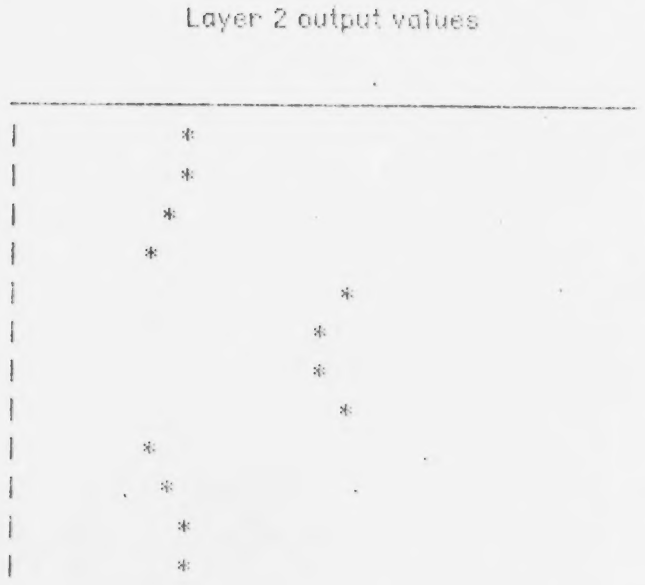

Fig. 9

on the spreadsheet from Figure 7 has been scrolled to the right and the display shows a plot of the transmitter cell output values. To prevent the user from having to search all over the spreadsheet for plotted points, each second layer transmitter output value has been divided by the maximum second layer transmitter output and then scaled to fit the size of the display. The location of each asterisk is determined by a formula which fills each cell with a computed number of blank spaces concatentated with an asterisk. Although the plotting is done on transformed scores and the axes of the graph have been rotated 90 degrees from their conventional orientation, the user can see in this plot a graphic analog corresponding to the visual experience reported by those who view the patch of red against a green background.

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Conclusion

The example described here by no means exhausts the phenomena which could be modeled using a spreadsheet program. For example, an earlier paper [3] illustrated how an electronic spreadsheet could be used in modeling the type of neural network responsible for the visual effects of Mach bands. (Mach bands are a series of adjacent, increasingly brighter bands of gray. Each band appears to differ in brightness from one edge of the band to the other. However, each band is, in fact, uniform in brightness across its width.) That same spreadsheet example can also be used for the exploration of the effects of contour sharpness. Furthermore, it appears to be entirely feasible to use a spreadsheet in developing template matching models of pattern recognition, or in modeling the process of feature analysis and detection. In fact, the author is presently preparing a report on a spreadsheet model of a bi-directional motion detector.

In addition, there are a number of complexities which could be introduced into the simulation described here if desired. For example, it has been assumed in the spreadsheet models discussed above that the input to the receptor cells is in units of stimulation required to produce the corresponding number of neural impulses per second. Other simplifications include representing only three layers of neural cells, using only a single row of receptor cells in the receptive field, having only one "red" and one "green" receptor in each first level circuit, having identical circuits throughout the network, *etc.* These, however, are not necessary simplifications. An electronic spreadsheet program easily allows the use of a functional relationship other than identity between the level of stimulation and the response rate of the receptors. Furthermore, the typical electronic spreadsheet is powerful enough to deal with the additional complexity and detail involved in having a variety of circuits at each level and in adding still more rows and/or more layers of cells to the simulation.

To date, student reactions to the neural model simulations described here, and in an earlier paper [3], have generally been favorable. These reactions, however, have been collected in a context of formative evaluation. Consequently, there are no experimental data to suggest the simulations have any particular worth or offer a student something which can not be gained

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through more traditional modes of presentation. Nonetheless, student comments clearly indicate three things which also appear to be true for simulations in general. First, a pre-use discussion and a post-use debriefing, in lecture or tutorial sessions, seem to enhance the effectiveness of the simulations. Second, some limitations of the simulations can be compensated for by proper pre-use preparation and post-use debriefing. Third, many students do feel they gain an enhanced depth and quality of understanding from the interactive learning and immediate feedback. Those who do not feel this way seem to be either those who felt they already understood the material or those who were confused by some aspect of the underlying material or by the way it was represented in the simulation. On balance then, the formative evaluations suggest that the exercises have some value in offering students who choose to do them a way of actively interacting with the material rather than just passively reading about it. (A few students have actually admitted to having fun exploring the simulations.)

One advantage of using a personal computer and the electronic spreadsheet in doing this kind of modeling is that each student can be given a copy of the spreadsheet template and asked to explore various aspects of the model. For example, since the lateral connections between layer one and layer two in the example used above extend only two cells to either side, one might wonder what the effects would be on the plot of transmitter firing rates if one were to widen the patch of red. The pattern of stimuluation can be changed and the spreadsheet program will recalculate and plot the new values. Similarly, a student who can access formulas in the spreadsheet cells can change gain factor values, add or delete cells in a circuit, introduce diffences within the circuits at each level, and generally modify the simulation in a variety of ways.

Thus the type of simulation described here creates an opportunity for active student exploration of a moderately complex neural network in ways which cost the student very little except in time spent learning. This is especially true when the student already owns a personal microcomputer and the spreadsheet program. In addition, the student is able to "experiment" with the simulation. Experiment both in the sense of discovering the characteristics of an unknown model and in the sense of modifying various components of a known model to see how the simulation is affected. Further,

a student is able to work with neural models and basic components in ways which allow for a natural generalization to the models and explanations required to deal with still more complex situations or phenomena.

For example, there is a rather fundamental and interesting complexity associated with induced color contrast which the simulation described here fails to model. The model will only work for two colors, red and green, but the phenomena of induced color contrast can be demonstrated for the full spectrum of colors and for any two complementary colors What makes the problem intriguing is that there are only three distinct populations of color receptors in the human eye--cones maximally sensitive to "red" light, cones maximally sensitive to "green" light and cones maximally sensitive to "blue" light. This implies the existence of some rather more complex neural circuitry than has been represented in the example presented here. Nonetheless, it is well within the capabilities of an electronic spreadsheet program to create the more complex neural model required to handle this problem. In addition, the level of programming expertise required by a spreadsheet program is low enough that an interested student can utilize those capabilities to take an inadequate neural model one or more steps further in an attempt to create a more adequate model, thereby actively engaging in the process of theoretical modeling.

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	3	4	5	6	7	8	9
1							
2	Receptor			Receptor			
3	Input			Output			
4							
5	0	-->	Red(1)	=IF(R5C3<1000,R5C3,"OUCH!")			
6	0	-->	Green(1)	=IF(R6C3<1000,R6C3,"OUCH!")		T(1)	=R5C6-R6C6+200
7	0	-->	Red(2)	=IF(R7C3<1000,R7C3,"OUCH!")			
8	0	-->	Green(2)	=IF(R8C3<1000,R8C3,"OUCH!")		T(2)	=R7C6-R8C6+200
9	0	-->	Red(3)	=IF(R9C3<1000,R9C3,"OUCH!")			
10	0	-->	Green(3)	=IF(R10C3<1000,R10C3,"OUCH!")		T(3)	=R9C6-R10C6+200
11	0	-->	Red(4)	=IF(R11C3<1000,R11C3,"OUCH!")			
12	0	-->	Green(4)	=IF(R12C3<1000,R12C3,"OUCH!")		T(4)	=R11C6-R12C6+200
13	0	-->	Red(5)	=IF(R13C3<1000,R13C3,"OUCH!")			
14	0	-->	Green(5)	=IF(R14C3<1000,R14C3,"OUCH!")		T(5)	=R13C6-R14C6+200
15	0	-->	Red(6)	=IF(R15C3<1000,R15C3,"OUCH!")			
16	0	-->	Green(6)	=IF(R16C3<1000,R16C3,"OUCH!")		T(6)	=R15C6-R16C6+200
17	0	-->	Red(7)	=IF(R17C3<1000,R17C3,"OUCH!")			
18	0	-->	Green(7)	=IF(R18C3<1000,R18C3,"OUCH!")		T(7)	=R17C6-R18C6+200
19	0	-->	Red(8)	=IF(R19C3<1000,R19C3,"OUCH!")			
20	0	-->	Green(8)	=IF(R20C3<1000,R20C3,"OUCH!")		T(8)	=R19C6-R20C6+200
21	0	-->	Red(9)	=IF(R21C3<1000,R21C3,"OUCH!")			
22	0	-->	Green(9)	=IF(R22C3<1000,R22C3,"OUCH!")		T(9)	=R21C6-R22C6+200
23	0	-->	Red(10)	=IF(R23C3<1000,R23C3,"OUCH!")			
24	0	-->	Green(10)	=IF(R24C3<1000,R24C3,"OUCH!")		T(10)	=R23C6-R24C6+200
25	0	-->	Red(11)	=IF(R25C3<1000,R25C3,"OUCH!")			
26	0	-->	Green(11)	=IF(R26C3<1000,R26C3,"OUCH!")		T(11)	=R25C6-R26C6+200
27	0	-->	Red(12)	=IF(R27C3<1000,R27C3,"OUCH!")			
28	0	-->	Green(12)	=IF(R28C3<1000,R28C3,"OUCH!")		T(12)	=R27C6-R28C6+200

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	10	12	13
1	Layer 1		
2	Transmitter		
3	Output		
4			
5			
6	=IF(R6C9<0,0,R6C9)	T(1)	=R6C10*(-0.1)+R6C10*(-0.1)+R6C10+R8C10*(-0.1)+R10C10*(-0.1)+100
7			
8	=IF(R8C9<0,0,R8C9)	T(2)	=R8C10*(-0.1)+R6C10*(-0.1)+R8C10+R10C10*(-0.1)+R12C10*(-0.1)+100
9			
10	=IF(R10C9<0,0,R10C9)	T(3)	=R6C10*(-0.1)+R8C10*(-0.1)+R10C10+R12C10*(-0.1)+R14C10*(-0.1)+100
11			
12	=IF(R12C9<0,0,R12C9)	T(4)	=R8C10*(-0.1)+R10C10*(-0.1)+R12C10+R14C10*(-0.1)+R16C10*(-0.1)+100
13			
14	=IF(R14C9<0,0,R14C9)	T(5)	=R10C10*(-0.1)+R12C10*(-0.1)+R14C10+R16C10*(-0.1)+R18C10*(-0.1)+100
15			
16	=IF(R16C9<0,0,R16C9)	T(6)	=R12C10*(-0.1)+R14C10*(-0.1)+R16C10+R18C10*(-0.1)+R20C10*(-0.1)+100
17			
18	=IF(R18C9<0,0,R18C9)	T(7)	=R14C10*(-0.1)+R16C10*(-0.1)+R18C10+R20C10*(-0.1)+R22C10*(-0.1)+100
19			
20	=IF(R20C9<0,0,R20C9)	T(8)	=R16C10*(-0.1)+R18C10*(-0.1)+R20C10+R22C10*(-0.1)+R24C10*(-0.1)+100
21			
22	=IF(R22C9<0,0,R22C9)	T(9)	=R18C10*(-0.1)+R20C10*(-0.1)+R22C10+R24C10*(-0.1)+R26C10*(-0.1)+100
23			
24	=IF(R24C9<0,0,R24C9)	T(10)	=R20C10*(-0.1)+R22C10*(-0.1)+R24C10+R26C10*(-0.1)+R28C10*(-0.1)+100
25			
26	=IF(R26C9<0,0,R26C9)	T(11)	=R22C10*(-0.1)+R24C10*(-0.1)+R26C10+R28C10*(-0.1)+R26C10*(-0.1)+100
27			
28	=IF(R28C9<0,0,R28C9)	T(12)	=R24C10*(-0.1)+R26C10*(-0.1)+R28C10+R28C10*(-0.1)+R28C10*(-0.1)+100

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	14	16	17
1	Layer 2		
2	Transmitter		
3	Output		Layer 2 output values
4			(Normalized to scale of 35.)
5			
6	=IF(R6C13<0,0,R6C13)		=REPT(" ",((R6C14/MAX(C14))*35))&"*"
7			=REPT(" ",((R8C14/MAX(C14))*35))&"*"
8	=IF(R8C13<0,0,R8C13)		=REPT(" ",((R10C14/MAX(C14))*35))&"*"
9			=REPT(" ",((R12C14/MAX(C14))*35))&"*"
10	=IF(R10C13<0,0,R10C13)		=REPT(" ",((R14C14/MAX(C14))*35))&"*"
11			=REPT(" ",((R16C14/MAX(C14))*35))&"*"
12	=IF(R12C13<0,0,R12C13)		=REPT(" ",((R18C14/MAX(C14))*35))&"*"
13			=REPT(" ",((R20C14/MAX(C14))*35))&"*"
14	=IF(R14C13<0,0,R14C13)		=REPT(" ",((R22C14/MAX(C14))*35))&"*"
15			=REPT(" ",((R24C14/MAX(C14))*35))&"*"
16	=IF(R16C13<0,0,R16C13)		=REPT(" ",((R26C14/MAX(C14))*35))&"*"
17			=REPT(" ",((R28C14/MAX(C14))*35))&"*"
18	=IF(R18C13<0,0,R18C13)		
19			
20	=IF(R20C13<0,0,R20C13)		
21			
22	=IF(R22C13<0,0,R22C13)		
23			
24	=IF(R24C13<0,0,R24C13)		
25			
26	=IF(R26C13<0,0,R26C13)		
27			
28	=IF(R28C13<0,0,R28C13)		